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Historical Note: Early Anthropological Contributions to "Geometric Morphometrics"

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The past decade has witnessed a proliferation of new quantitative methods for describing and comparing the shapes or forms (sizes plus shapes) of organisms (Rohlf and Marcus, 1993). Many of these techniques have been identified as belonging to a class of methods called "geometric morphometrics" (Bookstein, 1978), which explicitly preserve the geometric relationships among homologous landmarks, as reflected by their positions in two- or three-dimensional Cartesian coordinate space. The purpose of this communication is to discuss the early history of geometric morphometrics, with the intent of establishing a broader appreciation of the results of two early studies (Boas, 1905; Phelps, 1932) that are rarely, if ever, cited by modern scientists. In addition to giving credit where it is due, I hope to demonstrate that some early anthropologists had intellectual motivations in common with scientists working today.

Many geometric morphometric studies have made use of registration systems when comparing samples or assessing within-sample variation in form or shape. Registration systems are intended to place organisms into a common frame of reference, so that arbitrary differences in orientation are not erroneously interpreted as biologically meaningful differences in form. A registration system that is familiar to biological anthropologists is the Frankfurt Horizontal, designed for comparisons of human skull form (Fig. 1). Skulls are translated until the landmark porion (the superior aspect of the bony ear canal) coincides with the origin of a two-dimensional coordinate system. Each skull is then rotated so that a chord constructed between porion and orbitale (on the inferior rim of the orbit) coincides with the coordinate system's horizontal axis. Differences in the location of landmarks in this "registered" space are interpreted as differences in skull form.

The use of registration systems has recently been a point of contention among morphometricians. While some geometric, but registration-based, techniques have been widely employed [e.g., by users of Bookstein's (1986, 1991) method of "shape coordinates"], many authors have noted that the use of registration systems may actually lead to distortions in the measurements of form, rather than providing an objective framework for comparison, as they are intended to do (Moyers and Bookstein, 1979; Bookstein, 1982; Cheverud and Richtsmeier, 1986; Richtsmeier and Cheverud, 1986; Lele, 1991). These authors outline several reasons why registration methods may make unrealistic biological assumptions, but the most important objection to registration systems is that their definitions are arbitrary and that different definitions may lead to incongruent interpretations regarding differences and variations in form. Richtsmeier (1985: Fig. 3.1) provides a particularly good example, reproduced here as Figure 2.

Because of the biological objections to reg-

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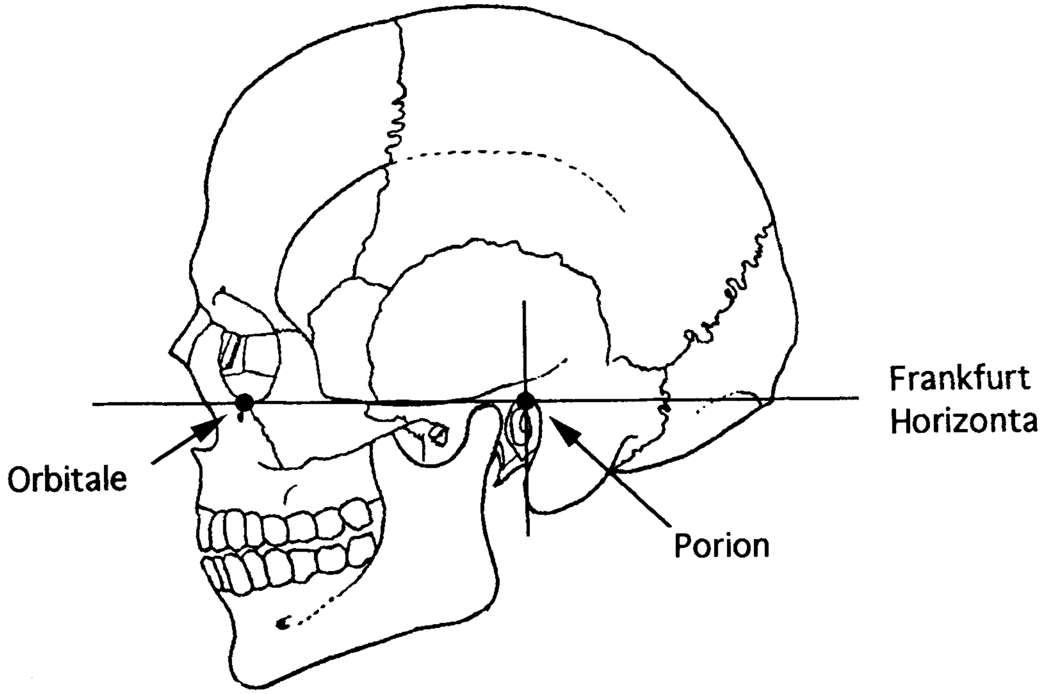

Fig. 1. A human skull registered according to the Frankfurt Horizontal. The landmark porion is the origin of the coordinate system, while the landmark orbitale defines the system's horizontal axis. This is perhaps the most widely-used point-line registration system for comparative craniometry. Adapted from Bass (1981: Fig. 32).

istration systems, researchers have been concerned with the development of "registration-free" methods of form comparison, including superimposition (Procrustes) methods (Sneath, 1967; Rohlf and Slice, 1990), finite element scaling analysis (Cheverud et al., 1983, 1991; Cheverud and Richtsmeier, 1986; Richtsmeier and Cheverud, 1986; Atchley et al., 1992; Vogl, 1993), thin-plate splines and relative warp analysis (Bookstein, 1989, 1991), and Euclidean distance matrix analysis (Lele, 1991; Lele and Richtsmeier, 1991; Lele, 1993). Each of these methods seeks not only to preserve the geometric integrity of the organism, but to eliminate the potential "user-inherent" biases that occur when arbitrary registrations are employed (Cheverud and Richtsmeier, 1986).

The study that is typically cited as the earliest application of "registration-free" morphometric methods is Sneath's (1967) application of superimposition (Procrustes) techniques in a comparison of the cranial shape of great apes and humans (both living and fossil). Sneath (1967) scaled, rotated, and translated skulls until corresponding landmarks were optimally approximated in a least-squares sense (Fig. 3). In the sections of Sneath's (1967) paper concerned with the least-squares fitting of skulls to a common coordinate system (Section 3; Appendixes 3.1, 3.2, and 3.3), there is no mention of previous work that attempted to compare configurations of landmarks via superimposition.

In fact, the earliest known applications of superimposition techniques to quantitative comparison of biological form were published not within the past 30 years, but shortly after the turn of the century. Bookstein (1994:202) has recently noted an appli-

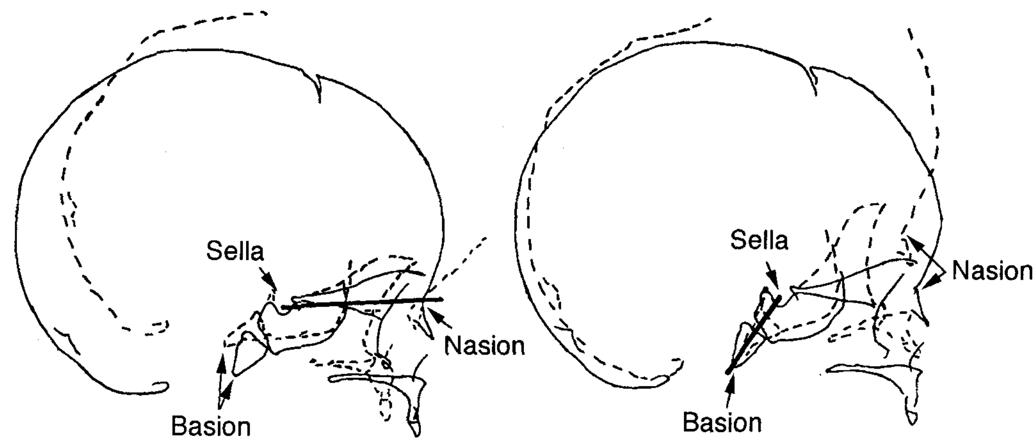

Fig. 2. Comparisons of the skull of a normal human with the skull of a patient with Apert's syndrome. Adapted from Richtsmeier (1985: Fig. 3.1). The comparison on the left uses a point-line registration system employing the landmarks sella and nasion, while the comparison on the right uses a sella-basion registration. Note that the two registration systems lead to different conclusions about the nature of shape differences between the two skulls (e.g., the size and position of the posterior cranial vault and the position of the palate). See Richtsmeier and Cheverud (1986) for a more detailed discussion of this example.

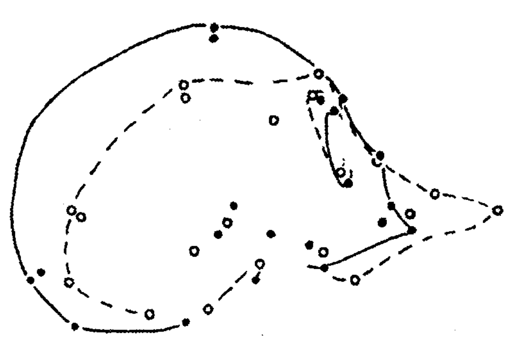

Fig. 3. An example of shape comparison using landmark-specific residuals, after least-squares fitting. A human skull (*Homo sapiens;* filled circles and solid outline) is compared to that of a chimpanzee (*Pan troglodytes;* hollow circles and dashed outline). Differences in shape are described in terms of the relative positions of corresponding landmarks in the *xy* plane. Adapted from Sneath (1967: Fig. 7).

cation of a registration method by Galton [1907, as related by Pearson (1930)] that is very similar to his method of "shape coordinates" (Bookstein, 1986, 1991). As remarkable as Galton's contribution was, an earlier paper not only described a method of geometric morphometrics, but explicitly addressed the biological artificiality of registration systems as well. The author was Franz Boas, who published his "method of least differences" in a 1905 issue of *Science.* Boas is widely recognized as the founder of the modern science of anthropology, with its "four-field" (sociocultural, biological, archeological, and linguistic) approach to questions of human diversity. However, his important contribution to morphometrics has been virtually ignored; I know of no citation of his work in the modern morphometric literature.

According to his student Eleanor Phelps (1932), Boas suffered from the same frustration with registration-based measurement strategies that would be felt by modern morphometricians many years later (e.g., Moyers and Bookstein, 1979; Bookstein, 1982; Cheverud et al., 1983; Cheverud and Richtsmeier, 1986; Richtsmeier and Cheverud, 1986). He recognized the biological artificiality of popular point-line registrations used in craniometry (e.g., the Frankfurt and French Horizontals), which assumed that a specific landmark was biologically "stable" enough, across different ages, sexes, and even taxa, to serve as the origin of a common coordinate system. Boas (1905:862) noted that "it will be recognized that there is no justification in selecting arbitrarily two points and disre-

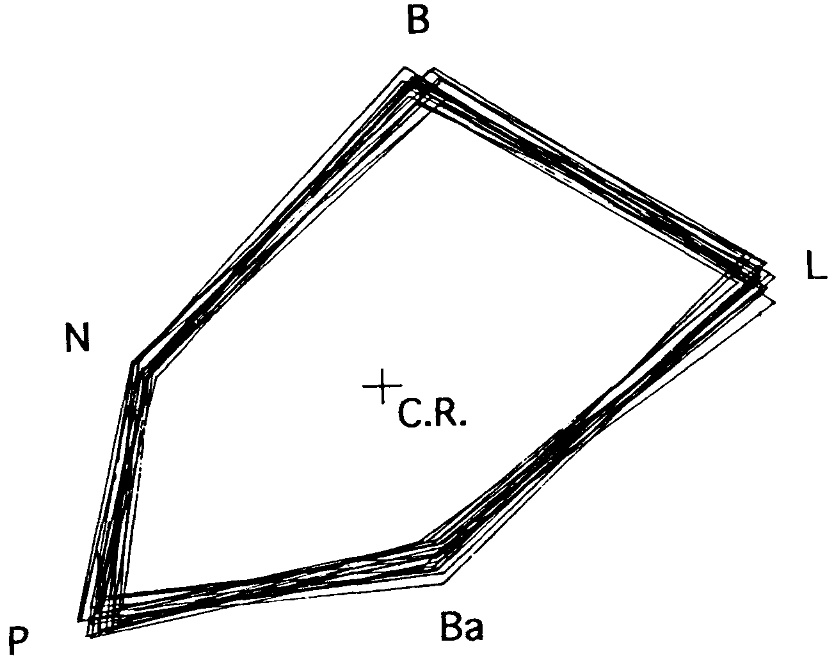

Fig. 4. An example of Boas' (1905) "method of least differences," as applied by Phelps (1932: modified from Fig. 5) to a sample of prehistoric Peruvian skulls. Anterior is to the left C.R. = center of reference (grand centroid); N = nasion: B = bregma; L = lambda; Ba = basion; P = prosthion. The midline projection of pterion is not shown.

garding all others, but that the best method of comparison must be based on the assumption that every point of the skull has equal weight and that the nearest approach of all points must be attempted." Boas' definition of the "best method of comparison" was as follows: "The most favorable superposition of any two forms will be obtained when the sum of the squares of the distances between all pairs of homologous points becomes a minimum" (1905:862). Boas thus anticipated Sneath's (1967) application of least-squares superimposition by more than 60 years!

Methodologically, Boas' (1905) application of least-squares fitting is nearly identical to Sneath's (1967) application. The important difference between Boas' (1905) method and later applications is that he made no adjustments for size differences between organisms. Thus, his superimposition method deals with variations in *form* (he explicitly uses this term) rather than *shape*. More modern applications of least-squares superimpositions and their robust variations almost invariably analyze shape variation by transforming all objects to the same scale (e.g., Sneath, 1967; Gower, 1971; Rohlf and Slice, 1990).

Eleanor Phelps applied Boas' method of least differences in her PhD dissertation and published a summary of her analysis in the *American Journal of Physical Anthropology* in 1932. Her paper cites no applications of Boas' (1905) method in the intervening years. She compared adult male skulls from three different populations (Australians, Eskimos, and Peruvians) using six craniometric landmarks (nasion, bregma, lambda, basion, prosthion, and a midline projection of pterion) (Fig. 4). Phelps (1932) extended Boas' method in interesting ways. First, she examined the effects of registration systems on variation at each landmark. After "fitting" (either to the Frankfurt or French Horizontals or by the method of least differences), a mean configuration was generated by calculating the averages of the respective x-

and y-components of each landmark. This is the same method of calculating a Procrustes mean used today (Rohlf and Slice, 1990). Variation about each landmark was quantified by calculating the respective x- and y-axis standard deviations at each landmark. She found that landmark-specific variation tended to decrease when the method of least differences was used; this is expected because a registration systems like the Frankfurt Horizontal does not seek to minimize variation over the whole of the form, while the method of least differences seeks to minimize variation at all points simultaneously. When a registration system is used, the natural variation in the points defining the system (e.g., porion and orbitale) is necessarily "spread" to other landmarks.

Phelps (1932) also used distance measures to quantify differences in form, anticipating the definition of "Procrustes distances" (Sneath, 1967; Gower, 1971; Rohlf and Slice, 1990) in spirit, if not in computational detail. Phelps (1932) proposed using the Euclidean distances between sample means at each landmark as measures of form difference (she did not calculate a distance over all landmarks).

Since the publication of Boas' paper more than 90 years ago, Phelps (1932) was, to my knowledge, the only person to apply least-squares superimposition in the years preceding Sneath (1967). Phelps' (1932) work, like Boas' (1905), anticipated many of the aspects of modern geometric morphometrics in spirit. Both authors recognized registration systems like the Frankfurt Horizontal is biologically arbitrary, a view held in common with many modern scientists. However, both papers would somehow fade into obscurity, despite their publications in major journals. One can only speculate as to why this happened. One possible reason is that many of the advances in quantitative methods made early in this century were made by statisticians (for example, Karl Pearson, who did extensive work in craniometrics; see Armelagos et al., 1982, for a review), rather than by anthropologists. In contrast, most early anthropologists took a typological approach to cranial variation, an approach that lasted well into the latter half of this century (Armelagos et al., 1982). Because it was computationally tedious, and because it broke with the well-established tradition of the Frankfurt Horizontal, Boas' method of least-differences was probably too much too soon. The relatively recent "rediscovery" of Boas' method (usually attributed to Sneath, 1967) and the current popularity of superimposition techniques only serve to underscore the importance of these contributions. Hopefully, Boas' (1905) and Phelps' (1932) publications will be more widely cited, so that the long history of geometric morphometrics, and the contribution of early anthropologists, will enjoy a broader appreciation.

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